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How experimentally to detect a solitary superconductivity in dirty ferromagnet-superconductor trilayers?

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ABSTRACT

We theoretically study the proximity effect in the thin-film layered ferromagnet (F) – superconductor (S) heterostructures in F_1F_2S design. We consider the boundary value problem for the Usadel-like equations in the case of so-called "dirty" limit. The "latent" superconducting pairing interaction in F layers taken into account. The focus is on the recipe of experimental preparation the state with so-called solitary superconductivity. We also propose and discuss the model of the superconducting spin valve based on F_1F_2S trilayers in solitary superconductivity regime.

1. Introduction

The coexistence of two antagonistic phenomena – superconductivity (S) and ferromagnetism (F) in artificial layered structures is possible due to the proximity effect [1]. The singlet superconducting condensate can penetrate from the S layer into the F layer, and nonmonotonically decays on very short distance about $\xi_I = \sqrt{D/2I}$ (where I is the exchange field and D is the diffusion coefficient in a ferromagnet) into the F layer. For strong ferromagnets such as Fe, Ni or Co the decay depth is approximately few nanometers. The peculiarity of the FS proximity effect and interplay between the S and F parameter orders give rise to a number of interesting phenomena and effects (see reviews [2–4] and the references therein), for example, the reentrant [5–7] and solitary superconductivity [8,9], nonmonotonic behaviors of the critical temperature T_c as function of the mutual alignment of the magnetizations of the F layers [10,11] and so on.

Rich physics of the FS proximity effect and rapid progress in area of the spintronics and superconducting electronics make this field promising for spin valve applications. For example, spin valve devices based on three-layer FS systems switched by a weak external magnetic field were proposed in [12–14]. In a recent experimental work [15] the difference $\Delta T(\alpha) = T_c(\alpha) - T_c(0^\circ)$ (where α is angle between magnetizations of the adjacent F layers) was measured in F_1F_2S (Fe/Cu/Fe/Cu/Pb) trilayer design. It has been shown that its highest value reached at the perpendicular magnetic alignment when $\Delta T(\alpha = 90^\circ) \approx 40$mK. Further, the difference $\Delta T(\alpha = 90^\circ) \approx 800$mK was achieved for a similar F_1F_2S (CrO_2/Cu/Ni/MoGe) system [16].

Earlier we theoretically investigate a solitary superconductivity for F_1F_2S system [7–9]. The solitary superconductivity corresponds to a localized region on the phase diagram of $T_c(d_f)$, in which $T_c > 0$ and thickness d_f belongs to region $[d_f^*, d_f^{**}]$, where $d_f^* > 0$. This occurs only at the antiparallel (AP) mutual magnetic aligned of F_1 and F_2 layers. The superconductivity does not occur at the parallel (P) orientation that makes relevant the study of states with solitary superconductivity, as they may prove to be the most promising for the superconducting spin valve applications.

In main goal this work is how experimentally to detect the solitary superconductivity.

2. Theoretical background

Near the superconducting transition the self-consistent equations for the superconducting order parameters has the form [1]

$$\Delta_i(\mathbf{r})\left(\ln t + \ln\frac{T_{cs}}{T_i}\right) = 2\pi T_c \mathrm{Re}\sum_{\omega>0}^{\infty}\left(F_i(\mathbf{r},\omega) - \frac{\Delta_i(\mathbf{r})}{\omega}\right), \quad i = (f1\,f2,s), \tag{1}$$

where $t = T_c/T_{cs}$ is the reduced critical temperature (T_{cs} and T_i is the superconducting critical temperature for the bulk material (S and F_i, respectively) without spin exchange interaction), ω is the Matsubara frequency.

The pair amplitudes $F_{s,(i)}$ satisfy the Usadel-like equations [17]

$$\left[|\omega| - iI_i - \frac{D_i}{2}\frac{d^2}{dx^2}\right]F_i(x,\omega) = \Delta_i(x). \tag{2}$$

Here I_i is the exchange interaction in F layers, D_i is the diffusion constant.

For pair amplitude F_i, we have Kupriyanov-Likichev like

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